VI. SABR FUEL CYCLE ANALYSIS

C. M. Sommer, W. Van Rooijen and W. M. Stacey, Georgia Tech

Abstract

Various fuel cycles for a sodium cooled, subcritical, fast reactor, SABR[1], with a fusion neutron source for the transmutation of light water reactor spent fuel have been analyzed. All fuel cycles were 4-batch, and all but one were constrained by a total fuel residence time consistent with a 200 dpa clad and structure materials damage limit. The objective of this study was to achieve greater than 90% burn up of the transuranics from the spent fuel, consistent with the Advanced Fuel Cycle objectives of DoE[2]. A more detailed account of this work can be found in the MS thesis of the first author[3].

A. SABR spent nuclear fuel transmutation reactor

SABR[1] is a TRU-metal-fueled, sodium cooled, subcritical fast transmutation reactor driven by a D-T fusion neutron source. Figure 1 shows a simplified three dimensional model of the reactor. An annular fission core contains metallic TRU fuel with initial weight percent composition of 40Zr-10Am-10Np-40Pu and maximum nominal operating temperature of 970 K. The core produces 3000MWth (83.3 kWth/kg TRU), with coolant nominal T_{in} = 650 K and T_{out} = 923 K. Reactivity decrease with fuel burnup is offset by increasing the fusion neutron source strength.

The fusion neutron source is surrounded on the outside by an annular fission core. Surrounding the fission core and the plasma there are tritium breeding blankets and several layers of shielding to protect the superconducting magnets that are used for the confinement of the plasma. The tokamak DT fusion neutron source for SABR is described in Ref. 4.

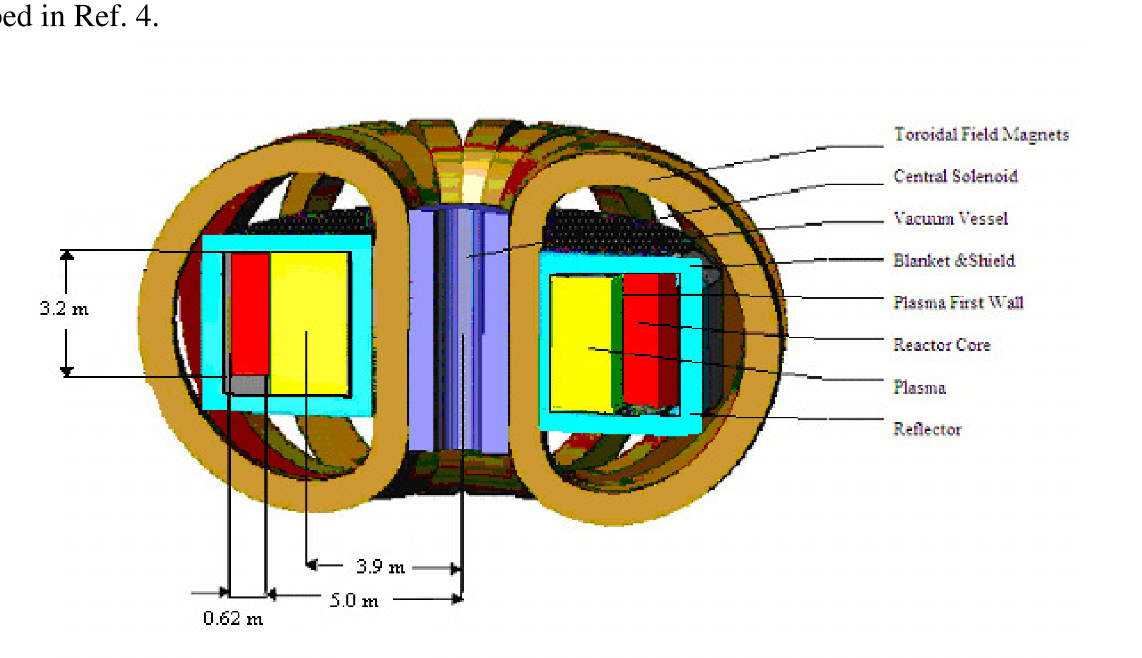

Figure 1: Configuration of SABR

B. Fuel cycle analysis

Five fuel cycle scenarios were investigated. The first two fuel cycle scenarios (A and B) examined the difference between in-to-out and out-to-in fuel shuffling for once-through fuel cycles (in the in-to-out scenario the fresh fuel batch is loaded next to the plasma source and shuffled successively outward, and vice-versa for the out-to-in scenario), and the third scenario (C) examined the effect of a design variation on power flattening. The fourth fuel cycle (D) examined the achievement of greater than 90% TRU burnup in a once-through fuel cycle, assuming the development of an advanced structural material that could withstand the associated radiation damage. Finally, the fifth fuel cycle (E) analysis, which is representative of the reference fuel cycle envisioned for advanced burner reactors (ABRs), examined the achievement of 90% TRU burnup by repeated reprocessing/recyling of the TRU fuel. The calculations for the fuel cycle of SABR were done by employing the TRITON/NEWT[5,6] package from SCALE5.1[7] and the neutronics code EVENT[8]. Cross sections were obtained fron NJOY[9]. A code was written to couple the cross section processing, the neutronics calculation and the depletion calculation in the fuel cycle.

A 4-batch fuel cycle was used in which the fuel resides for one burn cycle (of 750 days) in each of the four annular rings of the core, for a total fuel residence time (equal to 4 burn cycle times) of 3000 days, limited by the radiation damage to the clad and fuel assembly structure corresponding to 200 dpa. A "once-through" fuel cycle (in which "fresh" TRU fuel from SNF is loaded into one of the 4 rings at the beginning of each burn cycle and fuel which has been in residence for 4 burn cycles is removed and sent to a high level waste repository [HLWR]) achieves about 23% burnup (about 8.3 MT of TRU) before the fuel acquires 200 dpa and must be removed. A maximum $k_{eff} = 0.95$ occurs at beginning of life with fresh TRU fuel in all assemblies. Once such a fuel cycle reaches equilibrium, the values of k_{eff} at beginning and end of cycle (BOC and EOC) are about 0.90 and 0.85, which requires corresponding neutron source strengths in terms of P_{fusion} of about 180 and 240 MW, respectively, to maintain 3000 MWth fission power. The integral decay heat of the discharged fuel over 10^6 years is only reduced by a factor of about 2 (relative to the SNF discharged from LWRs) by such a "once-through" fuel cycle, implying a factor of 2 reduction in repository requirements. This fuel cycle provides a baseline of what can be accomplished without further reprocessing and recycling of the TRU fuel.

When the same 4-batch, 3000 day residence time fuel cycle is used but the fuel removed after 4 burn cycles is reprocessed and the TRU is recycled (together with "fresh" TRU from SNF), only the fission products and a small fraction of the actinides (0.15% Pu and Np, 0.03% Am) are sent to the HLWR after each reprocessing step. For such a "reprocessing" fuel cycle, the values of k_{eff} and P_{fusion} at BOC and EOC are about the same and the TRU burnup rates are slightly larger. The integral decay heat of material placed in a HLWR in such a reprocessing transmutation fuel cycle would be reduced to only 10% of the integral decay heat of the original SNF; i.e. the repository requirement is reduced by a factor of 10. SABR operating with 80% availability could support (i.e. burn the TRU in the discharged SNF of) four 1000 MWe LWRs.

If the 200 dpa radiation damage limit on fuel residence time could be relaxed, then greater TRU burnup could be achieved in a single residence time. A "once-though" fuel cycle as described in the first paragraph, but now with four 3000 day burn cycles and a fuel residence time of 12,000 days (24.65 yr) was found to burn up 91.2% of the TRU fuel. Once such a fuel cycle reaches equilibrium, the values of k_{eff} at BOC and EOC are about 0.68 and 0.48, which require corresponding neutron source strengths in terms of P_{fusion} of about 433 and 663 MW, respectively, to maintain 3000 MWth fission power. It is feasible to modify the SABR neutron source to produce more than the present P_{fusion} = 500 MW design limit. However, the integral decay heat of the remaining 8.8% of the TRU and the fission products (hence the HLWR requirement) is only reduced by a factor of about 3 relative to SNF discharged from LWRs, and the power was so strongly peaked near the neutron source in such a far subcritical reactor as to make the practical design of such a reactor unattractive.

The reference fuel cycle, in which the TRU fuel was reprocessed, mixed with fresh TRU fuel, and recycled into the reactor (with an "out-to-in" shuffling pattern) after each 24% burnup residence time, achieved greater than 90% TRU burnup after 9 residence times. The fuel ultimately discharged to the high level waste repository (HLWR) was reduced relative to the original spent nuclear fuel (SNF) from which it was produced by 99% in integral decay heat at 100,000 years after discharge. The resulting repository volume required for the millennial storage of the fuel discharged from the SABR was calculated to be 1/130 the volume that would have been required to store the original SNF from which that fuel was made. Detailed properties of this fuel cycle are given in Table 1.

Table 1 Reference fuel cycle parameters

Parameter	Units	Values
Thermal Power	MW	3000
Cycles per Residence Time		4
Burn Cycle Length Time	Days	750
4 Batch Residence Time	Years	8.21
BOC keff		0.900
EOC keff		0.847
BOC Pfus	MW	181
EOC Pfus	MW	241
TRU BOC Loading	MT	36
Power Density	KW/kg	83.3
Power Peaking BOC		1.28
Power Peaking EOC		1.54
TRU Burned per Residence	%	23.6%

TRU Burned per Year	MT/FPY	1.03
TRU Burned per Residence	MT	8.496
SNF Disposed per Year	MT/FPY	103
LWR Support Ratio		4
Average Core Flux Across Cycle	n/cm^2-s	1.47E16
Average Fast (>0.1 MeV) Flux	n/cm^2-s	9.20E15
Fluence per Residence Time	n/cm^2	3.81E24
Fast Fluence per Residence Time	n/cm^2	5.75E15
Hardness of Spectrum	%	62.6%
Heat Load at 100,000 years	W/kg TRU Initial	.00187
Heat Load at 100,000 years SABR Input	W/kg TRU Initial	.127
Integral Heat Load	W/kg TRU Initial	667
Integral Heat Load SABR Input	W/kg TRU Initial	88705
Passes For 90% Burn Up	#	9
Repository Space Gain	Factor	129

C. **Conclusions**

A 4 batch fuel cycle representative of the ABR's fuel cycle envisioned by GNEP was explored. This 4 batch, 3000 day cycle with repeated reprocessing and recycling of the TRU fuel to achieve greater than 90% burnup of the fuel after 9 recycles. The decay heat to the repository in this cycle would be short term and caused by the fission products. The increase in repository space by a factor of 129 is due to only 1% of the TRU having to be placed in the repository. This fuel cycle is the reference cycle for SABR. It was chosen as the reference cycle, because it meets all of the design criteria: 1) minimizes power peaking, 2) achieves a high transmutation rate and reaches 90% burnup of the TRU, 3) produces enough tritium to maintain self sufficiency, 4) decreases the long term decay heat, 5) and it reduces the repository requirements for spent nuclear fuel by a factor of 10.

References

1. W. M. Stacey, et al., "A TRU-Zr Metal Fuel, Sodium Cooled, Fast Subcritical Advanced Burner Reactor", *Nucl. Technol.*, 162, 53 (2008).

2. DoE Global Nuclear Energy Partnership website http://www.gnep.energy.gov
3. C. M. Sommer, "Fuel Cycle Analysis for SABR", MS Thesis, Georgia Institute of Technology, 2008.
4. J. P. Floyd, et al., "Tokamak Fusion Neutron Source for a Fast Transmutation Reactor", Fusion Sci. Technol., 52, 727 (2007).
5. "Triton: A Two-Dimensional Depletion Sequence for Characterization of Spent Nuclear Fuel," NUREG/CR-200, Rev. 5., Vol. I Section T1, ORNL/NUREG/CSD-2/R7 (2006).
6. "NEWT: A New Transport Algorithm For Two-Dimensional Discrete Ordinates Analysis In Non-Orthogonal Geometries," NUREG/CR-200, Rev. 5.1, Vol. II Section F21, ORNL/NUREG/CSD-2/R7 (2006).
7.. "SCALE5.1: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200, Rev. 5.1 (ORNL/NUREG/CSD-2/R5), Vold. I, II, and III, Oak Ridge National Laboratory/U.S. Nuclear Regulatory Commission (2006).
8. C. de OLIVEIRA and A.GODDARD, "EVENT—A Multi-dimensional Finite Element Spherical-Harmonics Radiation Transport Code," Proc. Int. Seminar *3-D Deterministic Radiation Transport Codes*, Paris, France, December 2–3, 1996, Organization for Economic Cooperation and Development (1996).
9. R.E. MACFARLANE & D.W. MUIR. "The NJOY Nuclear Data Processing System, Version 99," Los Alamos National Laboratory (1999